# Analyzing Test-As-You-Fly Single Event Upset (SEU) Responses using SEU Data, Classical Reliability Models, and Space Environment Data


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1.AS&D, Inc. in support of NASA/GSFC

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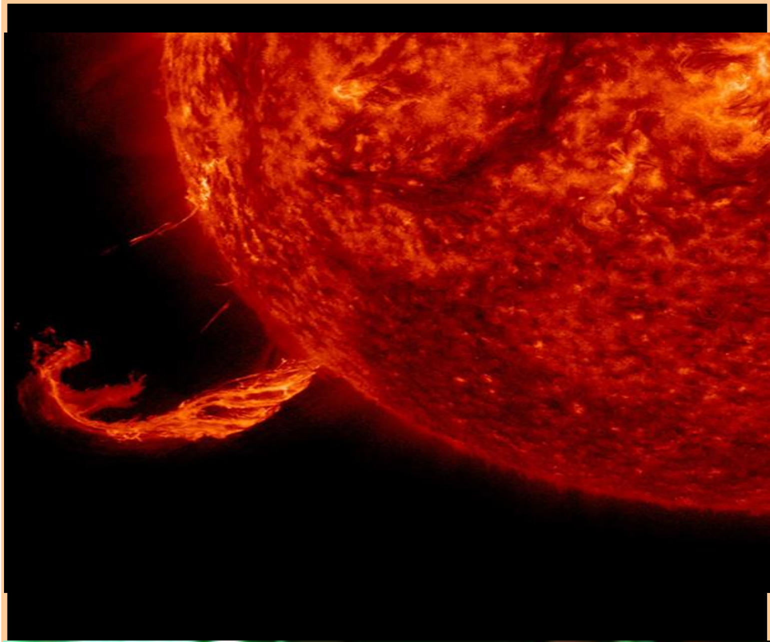
# Acronyms

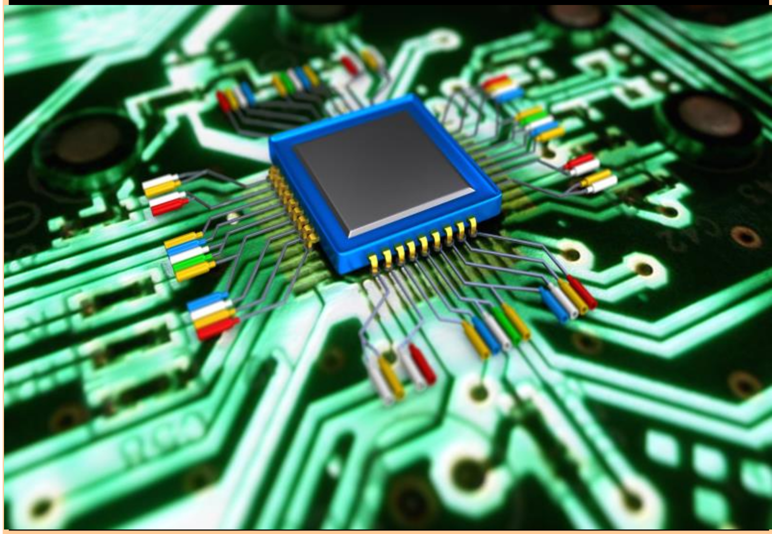
- Combinatorial logic (CL)
- Commercial off the shelf (COTS)
- Complementary metal-oxide semiconductor (CMOS)
- Device under test (DUT)
- Edge-triggered flip-flops (DFFs)
- Error rate ($\lambda$)
- Error rate per bit($\lambda_{bit}$)
- Error rate per system($\lambda_{system}$)
- Field programmable gate array (FPGA)
- Global triple modular redundancy (GTMR)
- Hardware description language (HDL)
- Input – output (I/O)
- Intellectual Property (IP)
- Linear energy transfer (LET)
- Mean fluence to failure (MFTF)
- Mean time to failure (MTTF)
- Operational frequency (fs)
- Personal Computer (PC)
- Probability of configuration upsets ($P_{configuration}$)
- Probability of Functional Logic upsets ($P_{functionalLogic}$)
- Probability of single event functional interrupt ($P_{SEFI}$)
- Probability of system failure ($P_{system}$)
- Processor (PC)
- Radiation Effects and Analysis Group (REAG)
- Reliability over time (R(t))
- Reliability over fluence (R($\Phi$))
- Single event effect (SEE)
- Single event functional interrupt (SEFI)
- Single event latch-up (SEL)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section ($\sigma_{SEU}$)
- Xilinx Virtex 5 field programmable gate array (V5)
- Xilinx Virtex 5 field programmable gate array radiation hardened (V5QV)

# Problem Statement

- **Conventional methods of single event upset (SEU) analysis are not effective for characterizing error rates (λ) or mean time to failure (MTTF) for complex systems implemented in field programmable gate array (FPGA) devices.**

- **The problem boils down to extrapolation and application of SEU data to characterize system performance in radiation environments.**





# Abstract

- We are investigating the application of classical reliability performance metrics combined with standard SEU analysis data.
- We expect to relate SEU behavior to system performance requirements…
  - Example: The system is required to be 99.999% reliable within a given time window. Will the system's SEU response meet mission requirements?
  - Our proposed methodology will provide better prediction of SEU responses in harsh radiation environments.

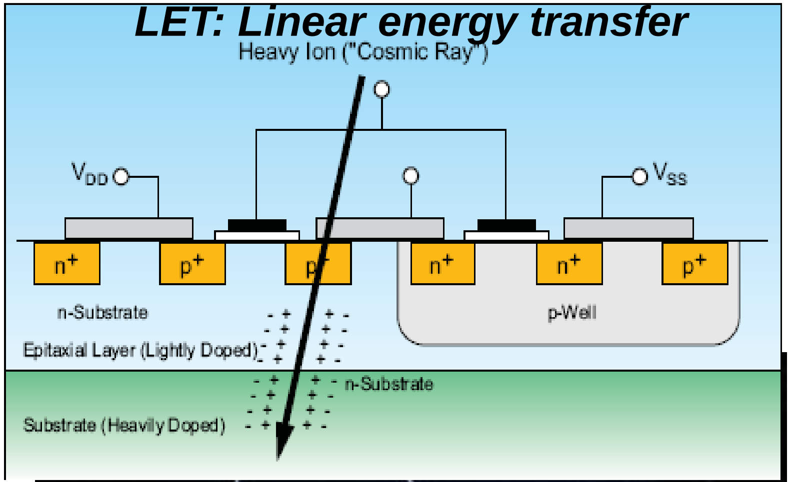
# Background
# (Traditional Method for SEU Calculations)

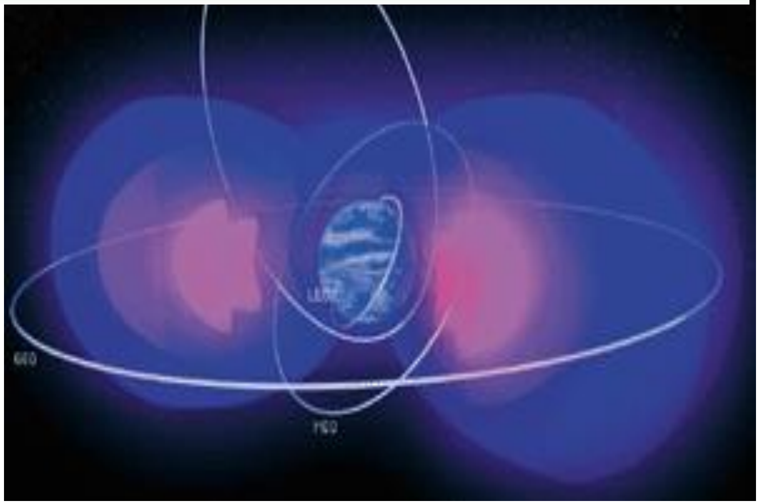
- **Conventional goal: Convert SEU cross-sections ($\sigma_{SEU}$: $cm^2$/(particles)) to error rates ($\lambda$) for complex systems.**
- **Common methods of SEU analysis include the following steps:**
  - **Perform SEU accelerated radiation testing across ions with different linear energy transfers (LETs) to calculate $\sigma_{SEU}$s per LET.**
  - **Given $\sigma_{SEU}$ (per bit) use an error rate calculator (such as CRÈME96) to obtain an error rate per bit ($\lambda_{bit}$);**
  - **Multiply $\lambda_{bit}$ by the number of used memory bits (*#UsedBits*) in the target design to attain a system error rate ($\lambda_{system}$).**

$$\lambda_{system} < \lambda_{bit} \times \#UsedBits$$

$$\sigma_{SEU} = \#errors/fluence$$

$$\lambda_{system} = \#errors/time$$



# Background
# FPGA SEE Susceptibility

- $\sigma_{SEU}$s (per category) are calculated from SEE test and analysis.
- Traditionally, global route contributions have been ignored.
- FPGAs vary and so do their SEU responses. However, the dominant $\sigma_{SEU}$s are usually per bit (configuration or functional logic).
- After the dominant $\sigma_{SEU}$ is determined, we multiply the calculated $\lambda_{bit}$ by the number of used bits (configuration or functional logic).

$\sigma_{SEU}$ are measured by bit

$\sigma_{SEU}$ are measured by bit

$$P(fs)_{system} \mu P_{Configuration} + P(fs)_{functionalLogic} + P_{SEFI}$$

Design $\sigma_{SEU}$

Configuration $\sigma_{SEU}$

Functional logic $\sigma_{SEU}$

SEFI $\sigma_{SEU}$

*Sequential and Combinatorial logic (CL) in data path*

*Global Routes and Hidden Logic*

*SEU cross section: $\sigma_{SEU}$*

*Error rate: $\lambda$*

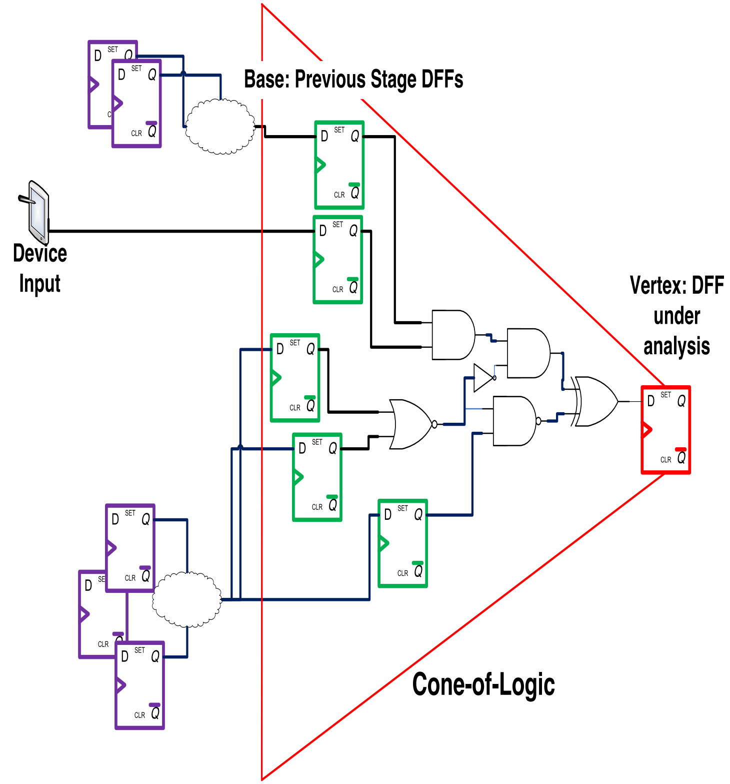
# Technical Problems with Current System Analysis Method (1)

- Multiplying each bit within a design by $\lambda_{bit}$ is not an efficient method of system error rate prediction.
  - Works well with memory structures… but…
  - Complex systems do not operate like memories.
  - If an SEU affects a bit, and the bit is either inactive, disabled, or masked, a system malfunction might not occur.
    - Using the same multiplication factor across DFFs will produce extreme over-estimates.
    - To this date, there is no accurate method to predict DFF activity for complex systems.
    - Fault injection or simulation will not determine frequency of activity.

$$\lambda_{system} < \lambda_{bit} \times \#UsedBits$$

# Technical Problems with Current System Analysis Method (2)

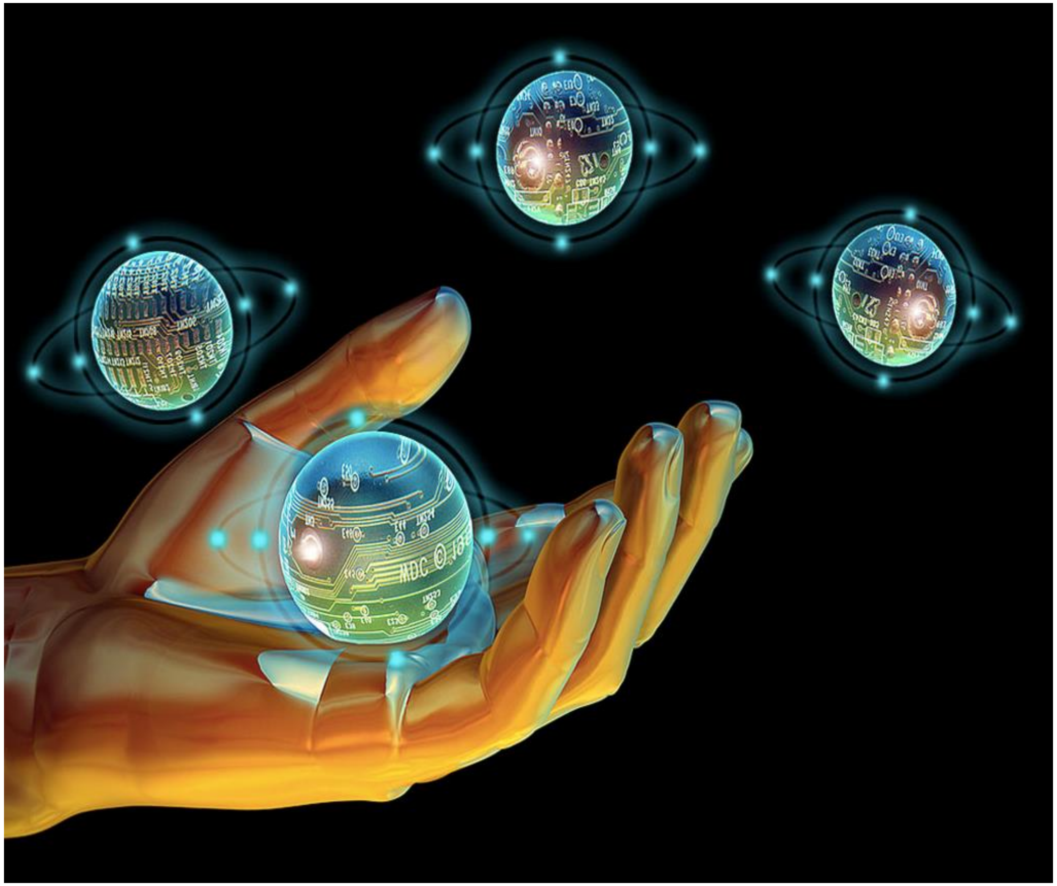
- **There are a variety of components that are susceptible to SEUs (clocks, resets, combinatorial logic, flip-flops (DFFs, etc…)).**
  - **Various component susceptibilities are not accurately characterized at a per bit level.**
  - **Design topology makes a significant difference in susceptibility and is not characterized in error rate calculators (e.g., CREME96).**




**Error rates calculated at the transistor-bit level are estimated at too small of granularity for proper extrapolation to complex systems.**

# Let's Not Reinvent The Wheel… A Proven Solution Can Be Found in Classical Reliability Analysis

- Classical reliability models have been used as a standard metric for complex system performance.
- The analysis provides a more in depth interpretation of system behavior over time by using system-level MTTF data for system performance metrics.



$$R(t)=e^{-t/MTTF} \text{ or } R(t)=e^{-\lambda t}$$

*Theory is already developed, proven, and should be in our hands!*

# A Comparison of Reliability and SEU Analyses

- Classical reliability models are measured across time.
  - This is because most of the failures that can affect performance in classical studies are due to wear-out mechanisms, or corner-case design bugs.
  - For each case, time to failure is a key measurement factor.
- When evaluating SEU susceptibility, during radiation testing, particle fluence is the key variable for system failure as opposed to time.
  - Missions required to operate in space environments will be susceptible to fluences ($\Phi$ particles/($cm^2$)) of ionizing particles .
  - As a metric of SEU susceptibility, $\sigma_{SEU}$s are calculated across fluence.
- Goal: In order to better characterize SEU susceptibility for complex systems, we would like to analyze given $\sigma_{SEU}$s per bit and $\sigma_{SEU}$s per system.

# Mapping Classical Reliability Models from The Time Domain To The Fluence Domain

- The exponential model that relates reliability to MTTF assumes that across time (disregarding infant mortality and wear-out): $R(t)=e^{-t/MTTF}$ or $R(t)=e^{-\lambda t}$
  - Failures are random.
  - Error rate is constant.
  - MTTF = $1/\lambda$.
- For a given LET (across fluence):
  - SEUs are random.
  - $\sigma_{SEU}$ is constant.
  - MFTF = $1/\sigma_{SEU}$.

*Parallel between time and fluence.*

$\sigma_{SEU}$ = #errors/fluence

$\lambda_{system}$ = #errors/time

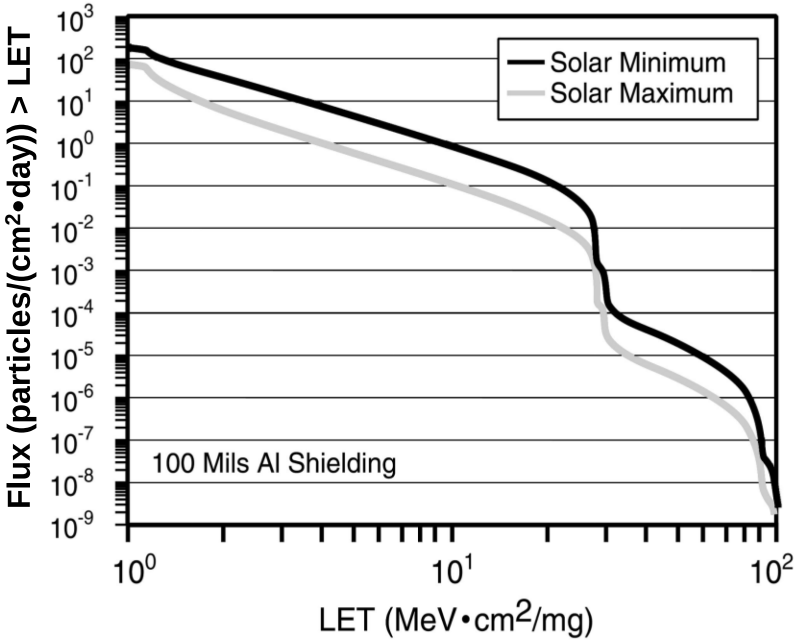
- Hence, mapping from the time domain to the fluence domain is straight forward:
  - $t \Leftrightarrow \Phi$
  - MTTF $\Leftrightarrow$ MFTF
  - $\lambda \Leftrightarrow \sigma_{SEU}$

$$R(t)=e^{-t/MTTF} \Leftrightarrow R(\Phi)=e^{\Phi/MFTF}$$

# Use of Environment Data

- Typical (heavy-ion) environment data is expressed in particle flux across LET.
- In many cases, missions want to know what is the reliability of a system, within a given a time window.
- When analyzing SEU system behavior, this can also be interpreted as: what is the reliability given a window of particle fluence.

*Flux : particles/(cm² •day)*




*M. A. Xapsos, IEEE NSREC Short Course, Ponte Vedra Beach, FL, 2008.*

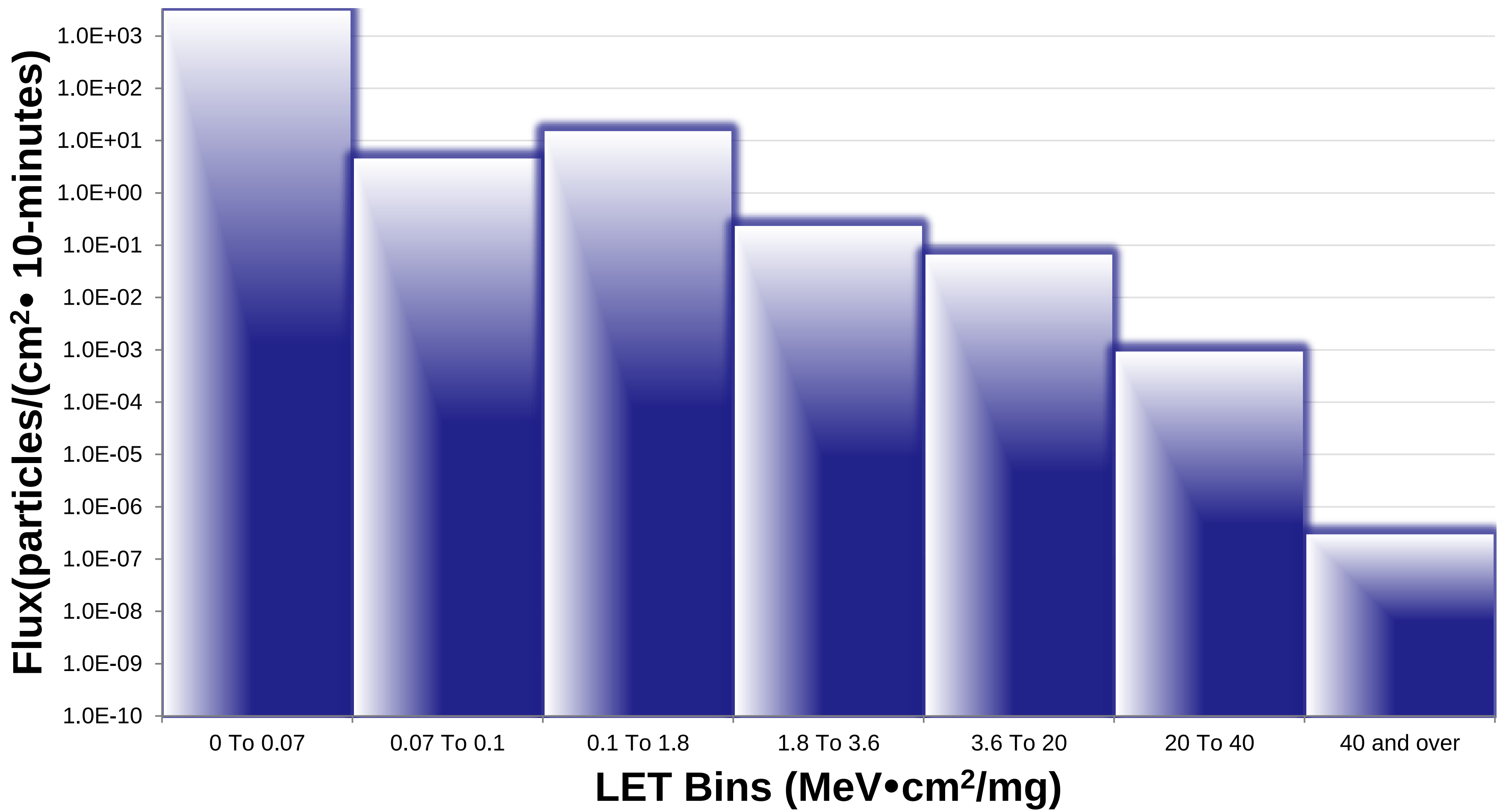
# Example

- **Mission requirements:**
  - **The FPGA shall contain an embedded microprocessor.**
  - **Decision shall be made to select a Xilinx V5QV (approximately $80,000 per device) or a Xilinx V5 with embedded PowerPC (less than $2000.00) per device.**
  - **FPGA operation shall have reliability of 3-nines (99.9%) within a 10 minute window.**
- **Proposed methodology:**
  - **Create a histogram of particle flux versus LET for a 10-minute window of time for your target environment.**
  - **Calculate MFTF per LET (obtain SEU data).**
  - **Graph R(Φ) for a variety of LET values and their associated MFTFs.** $R(\Phi)=e^{\Phi/MFTF}$
  - **For selected ranges of LETs, use an upper bound of particle flux (number of particles/cm$^2$•10-minutes), to determine if the system will meet the mission's reliability requirements.**

# Flux versus LET Histogram for A 10-minute Window

*Geosynchronous Equatorial Orbit (GEO)*

*100-mils shielding*

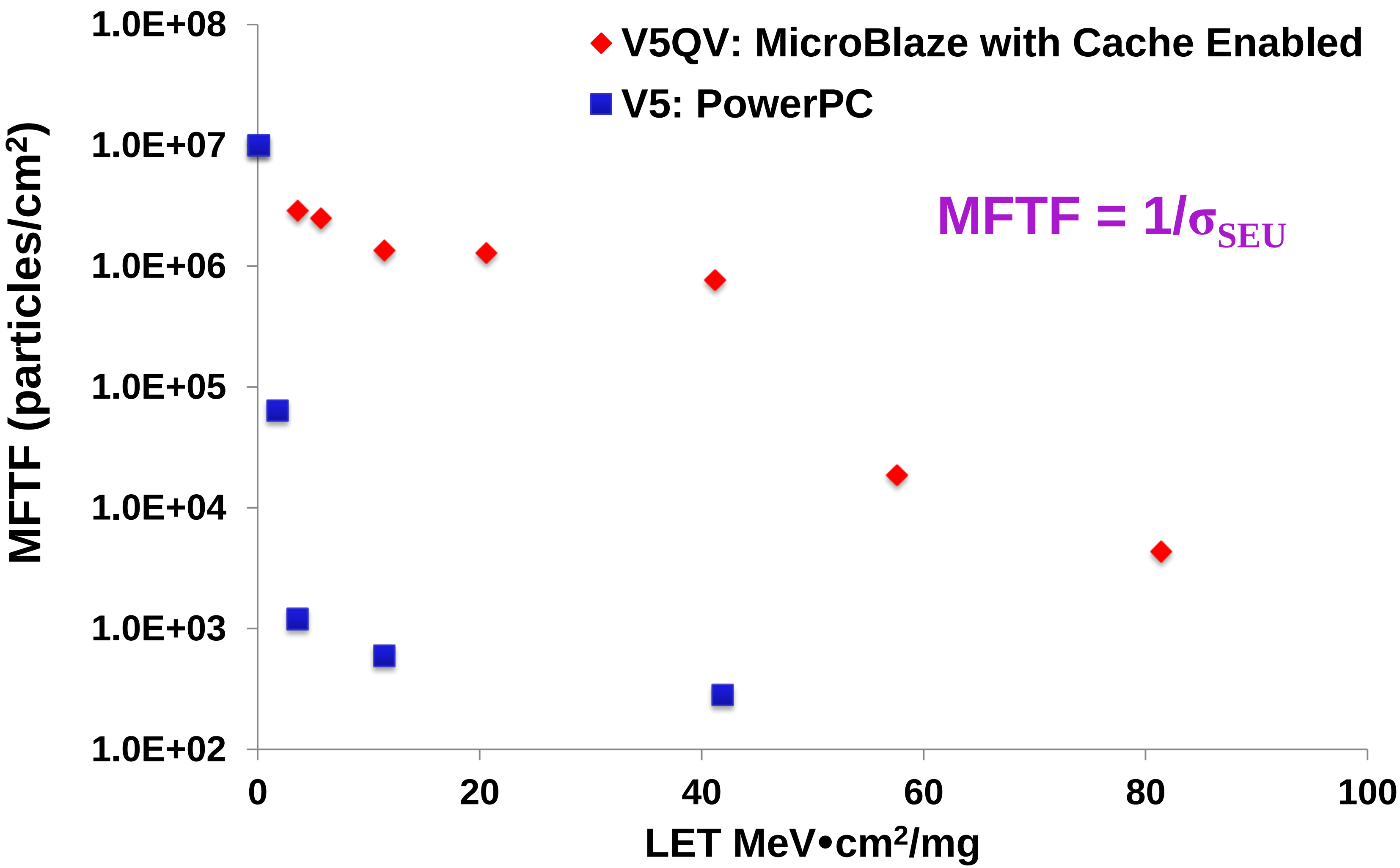


# Histogram Actuals: For Reference

Frequency distribution of LET (MeV-cm$^2$/mg)

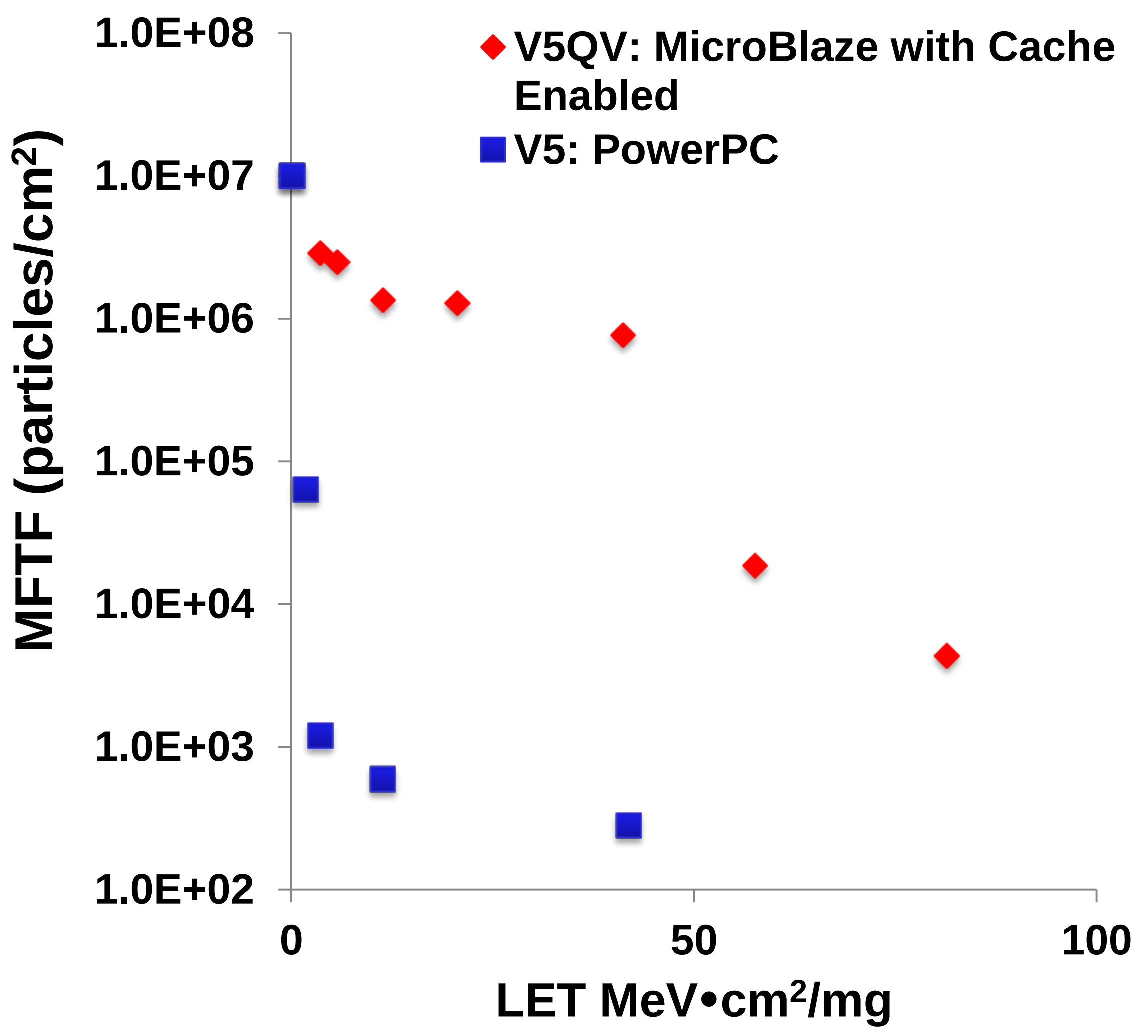
| LET (MeV-cm$^2$/mg) | *Flux (particles/(cm$^2$ •10minutes)* | *Cumulative Flux Count (particles/(cm$^2$ •10minutes)* | *Percent* | *Cumulative Percent* |
|---|---|---|---|---|
| *0 To 0.07* | 3,068.53038 | 3,068.53038 | 0.99352 | 0.99352 |
| *0.07 To 0.1* | 4.55258 | 3,073.08297 | 0.00147 | 0.99499 |
| *0.1 To 1.8* | 15.17444 | 3,088.2574 | 0.00491 | 0.9999 |
| *1.8 To 3.6* | 0.22905 | 3,088.48645 | 0.00007 | 0.99998 |
| *3.6 To 20* | 0.06566 | 3,088.55212 | 0.00002 | 1. |
| *20 To 40* | 0.00093 | 3,088.55304 | 2.99929E-7 | 1. |
| *40 and over* | 2.94342E-7 | 3,088.55304 | 9.5301E-11 | 1. |

# MFTF versus LET for the Xilinx V5 MicroBlaze Soft Processor Core and the Xilinx V5QV embedded PowerPC Core



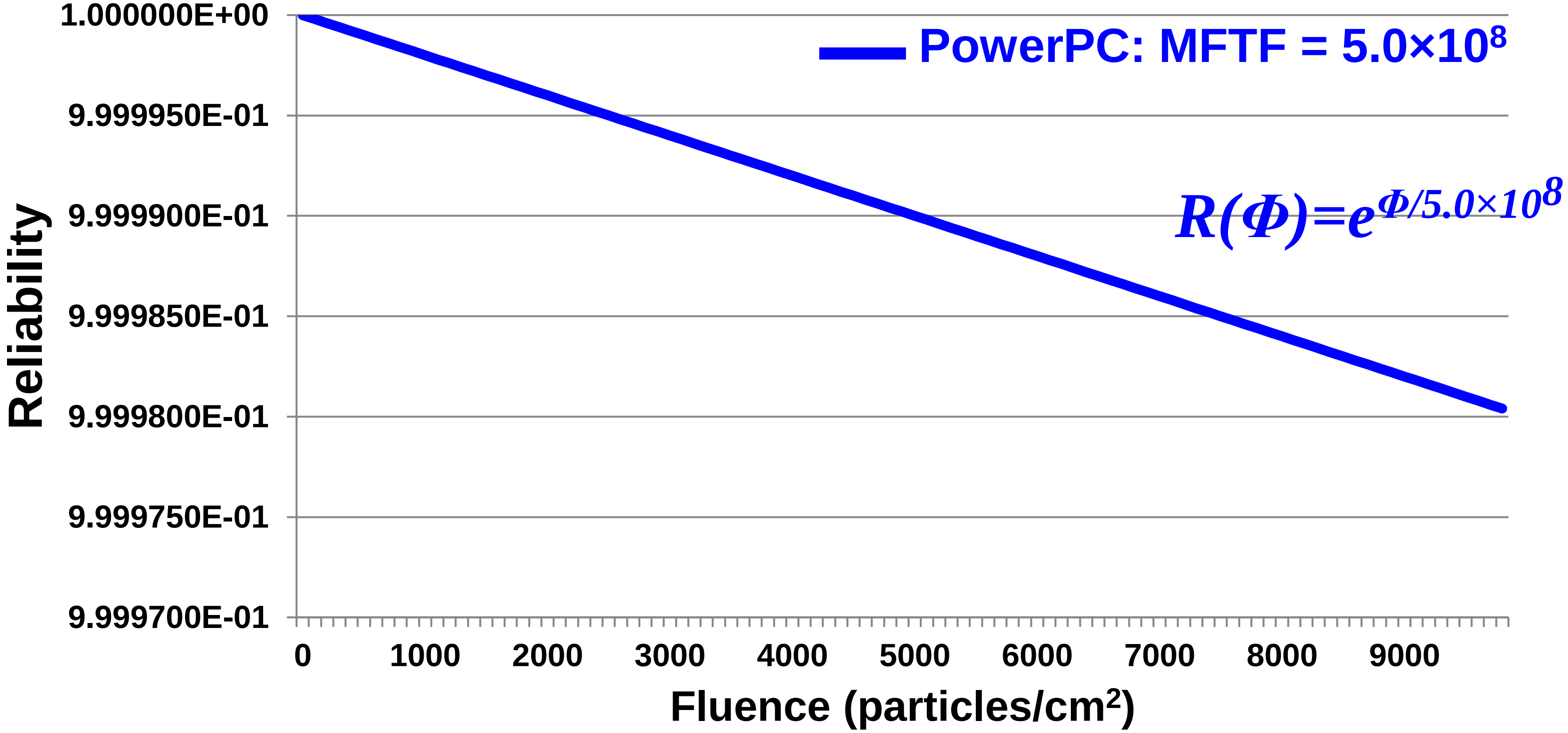
# Reliability across Fluence at LET=0.07MeV•cm²/mg And Below

- **V5QV:** no system errors were observed below LET=3.6MeV•cm²/mg. Total fluence > 5.0×10⁸ particles/cm².
- **PowerPC:**
  - System errors were observed with a MFTF=1×10⁷ particles/cm²at an LET=0.07MeV•cm²/mg.
  - No systems errors were observed at an LET=0.01MeV•cm²/mg with a Total fluence > 5.0×10⁸ particles/cm²



# Reliability across Fluence up to LET=0.07 MeV•cm²/mg – Low Bound Analysis

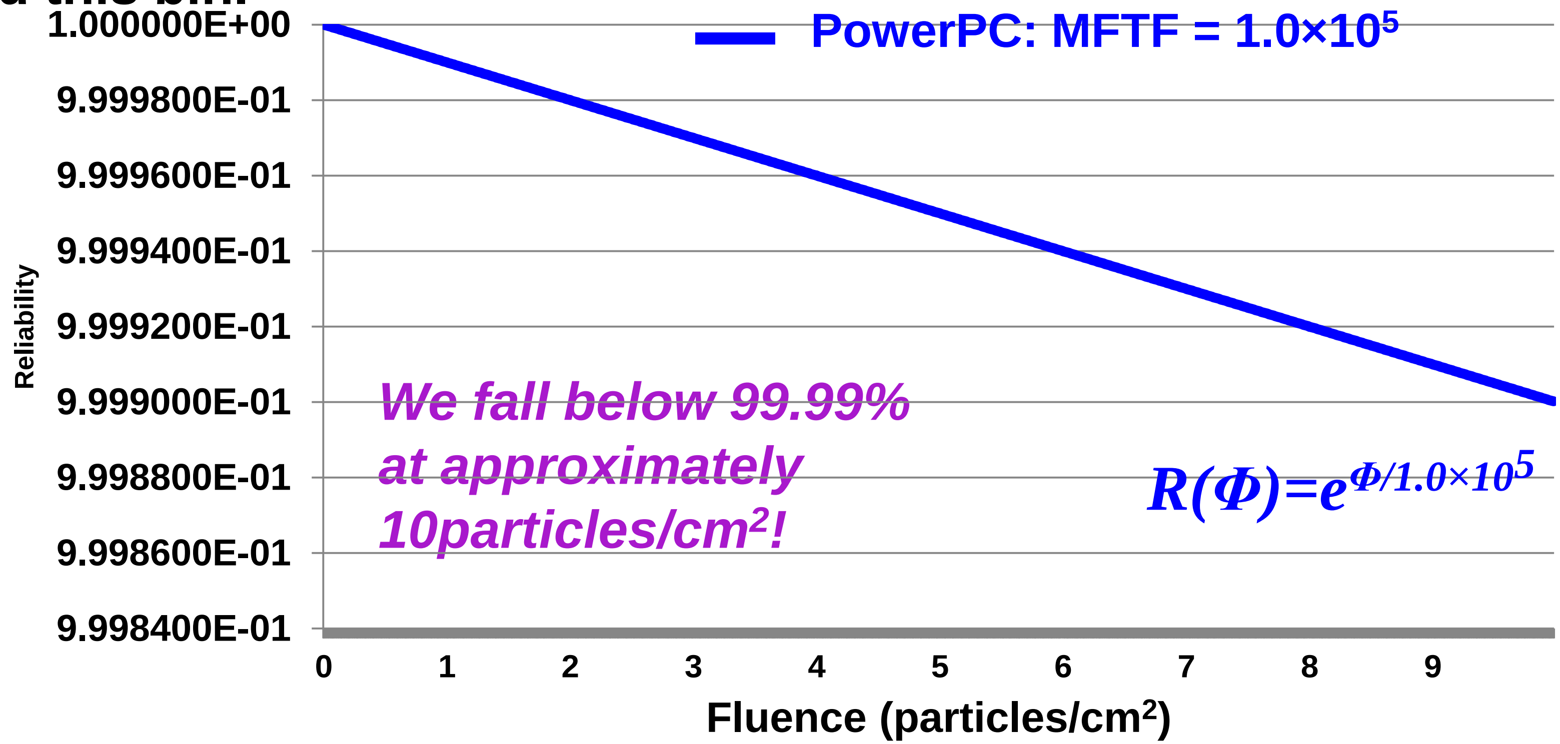
**Binned GEO Environment data shows approximately 3000 particles/(cm²•10-minutes), in the range of 0.0MeV•cm²/mg to 0.07MeV•cm²/mg. We are using MFTF for 0.07MeV•cm²/mg to upper bound this bin.**




**Reliability at 3000 particles/(cm²•10-minutes) > 99.999% for the PowerPC design implementation.**

# Reliability across Fluence up to LET=0.1 MeV•cm²/mg

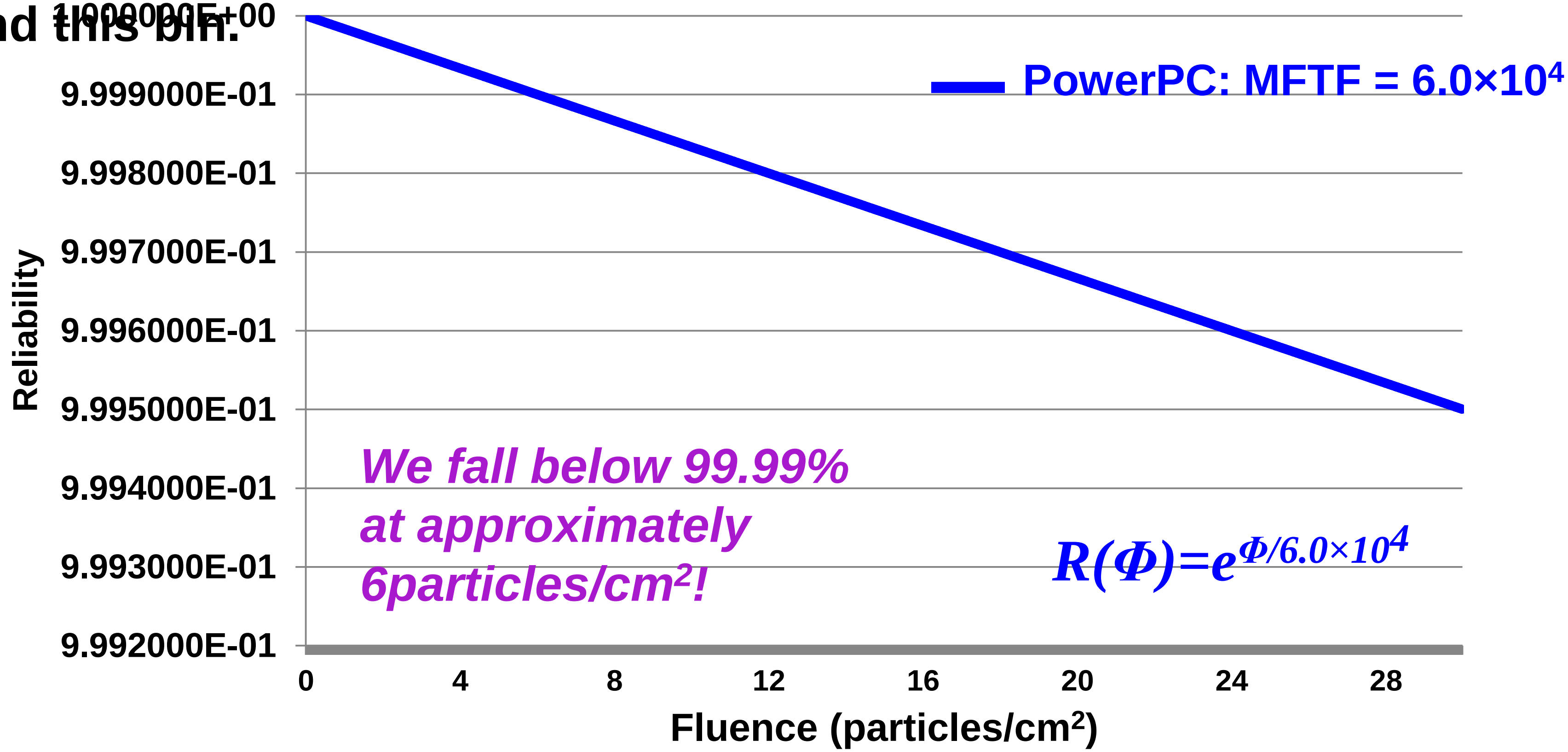
**Binned GEO Environment data shows approximately 5 particles/(cm²•10-minutes), in the range of 0.07MeV•cm²/mg to 0.1MeV•cm²/mg. We are using MFTF for 0.1MeV•cm²/mg to upper bound this bin.**




**Reliability at 5 particles/(cm²•10-minutes) > 99.99% for the PowerPC design implementation.**

# Reliability across Fluence up to LET=1.8 MeV•cm²/mg

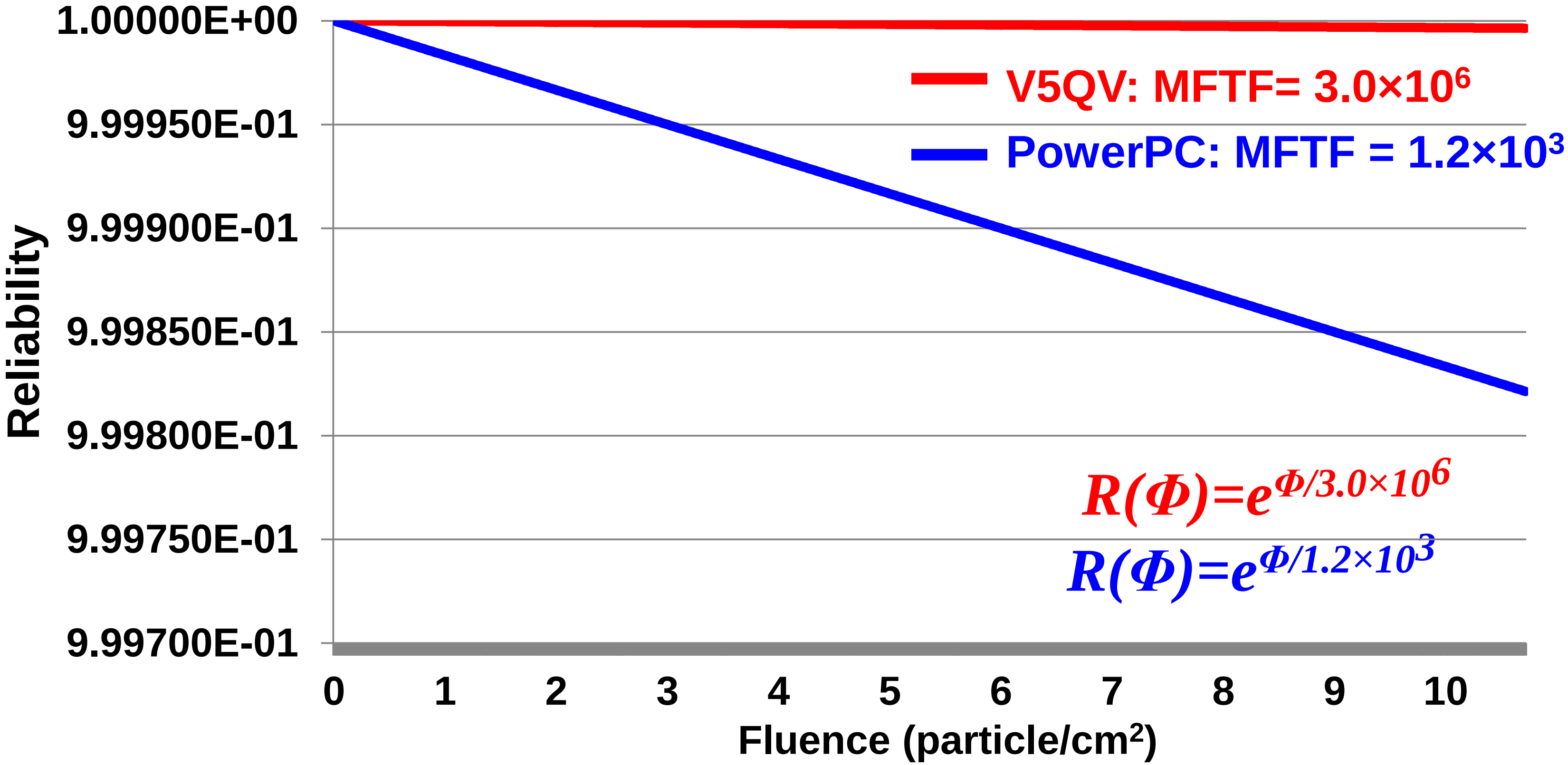
**Binned GEO Environment data shows approximately 15 particles/(cm²•10-minutes), in the range of 0.1MeV•cm²/mg to 1.8MeV•cm²/mg. We are using MFTF for 1.8MeV•cm²/mg to upper bound this bin.**




**Reliability at 15 particles/(cm²•10-minutes) > 99.9% for the PowerPC design implementation. This is the most susceptible bin for the system.**

# Reliability across Fluence up to LET=3.6MeV•cm²/mg

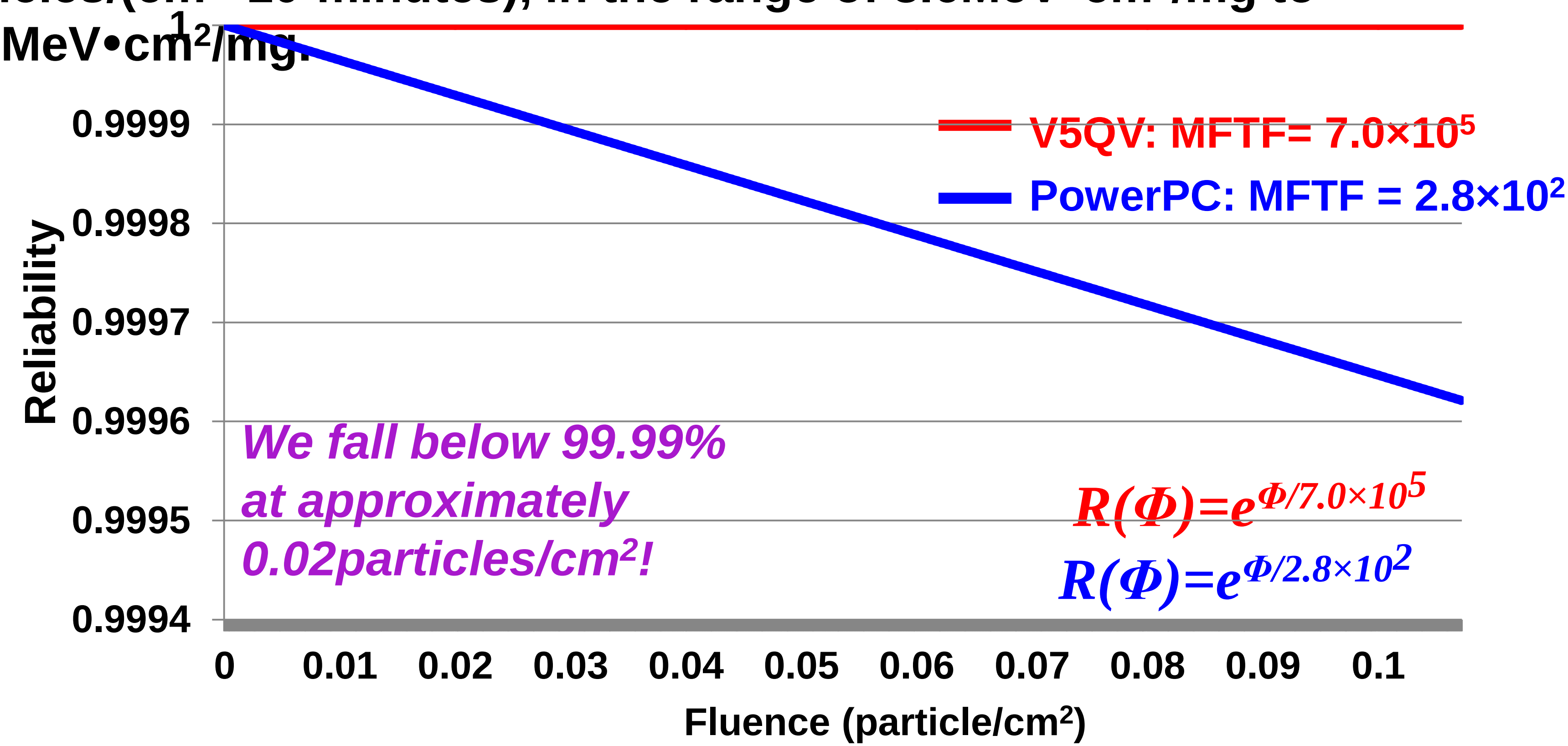
**Binned GEO Environment data shows approximately 0.23 particles/(cm²•10-minutes), in the range of 1.8MeV•cm²/mg to 3.6MeV•cm²/mg.**




**Within this LET range, reliability at 0.23 particles/(cm²•10-minutes) > 99.999% for both design implementations.**

# Reliability across Fluence at LET=40MeVcm²/mg

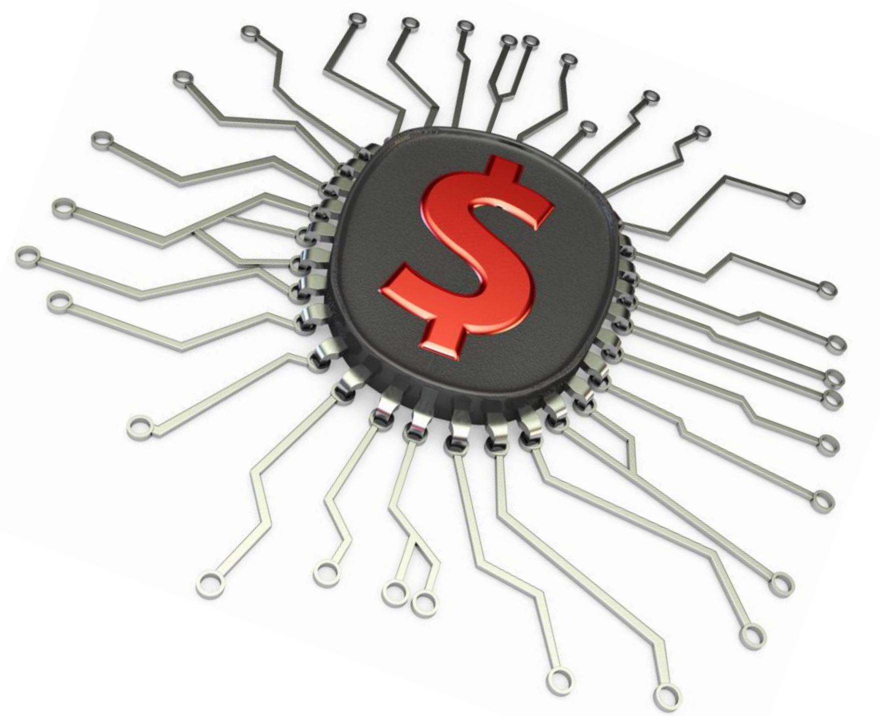
**Binned GEO environment data shows approximately 0.07 particles/(cm²•10-minutes), in the range of 3.6MeV•cm²/mg to 40.0MeV•cm²/mg.**




**Within this LET range, reliability at 0.07 particles/(cm²•10-minutes) > 99.9% for both design implementations. We can refine by analyzing smaller bins.**

# Example Conclusion

- Using the proposed methodology, the commercial Xilinx V5 device will meet project requirements.
- In this case, the project is able to save money by selecting the significantly cheaper FPGA device and gain performance because of the embedded PowerPC.



# Conclusions

- **This study transforms proven classical reliability models into the SEU particle fluence domain. The intent is to better characterize SEU responses for complex systems.**
- **The method for reliability-model application is as follows:**
  - **SEU data is obtained as MFTF.**
  - **Reliability curves (in the fluence domain) are calculated using MFTF; and are analyzed with a piecemeal approach.**
  - **Environment data is then used to determine particle flux exposure within required windows of mission operation.**
- **An example is provided to illustrate the strength of the proposed SEU characterization methodology.**
- **This is preliminary work. There is more in the plans.**

***This methodology expresses SEU behavior and response in terms that missions understand via classical reliability metrics.***

# Acknowledgements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